FOREWORD FOR FRIENDS AND RELATIVES

extracted from

A DIFFERENTIAL POPULATION SYNTHESIS APPROACH

TO

MASS SEGREGATION IN M92

by

WILLIAM JOHN TOBIN

Ph.D. thesis (Astronomy)
University of Wisconsin-Madison
1979

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A DIFFERENTIAL POPULATION SYNTHESIS APPROACH

TO

MASS SEGREGATION IN M92

A thesis submitted to the Graduate School of the
University of Wisconsin-Madison in partial fulfillment of
the requirements for the degree of Doctor of Philosophy

BY

WILLIAM JOHN TOBIN

Degree to be awarded: December 1979 May 19 August 19

Approved by Thesis Reading Committee:

Kenneth H. Nordsieck
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1979 October 11.
Date of Examination

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Dean, Graduate School

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WILLIAM JOHN TOBIN

A thesis submitted in partial fulfillment of the requirements for the degree of

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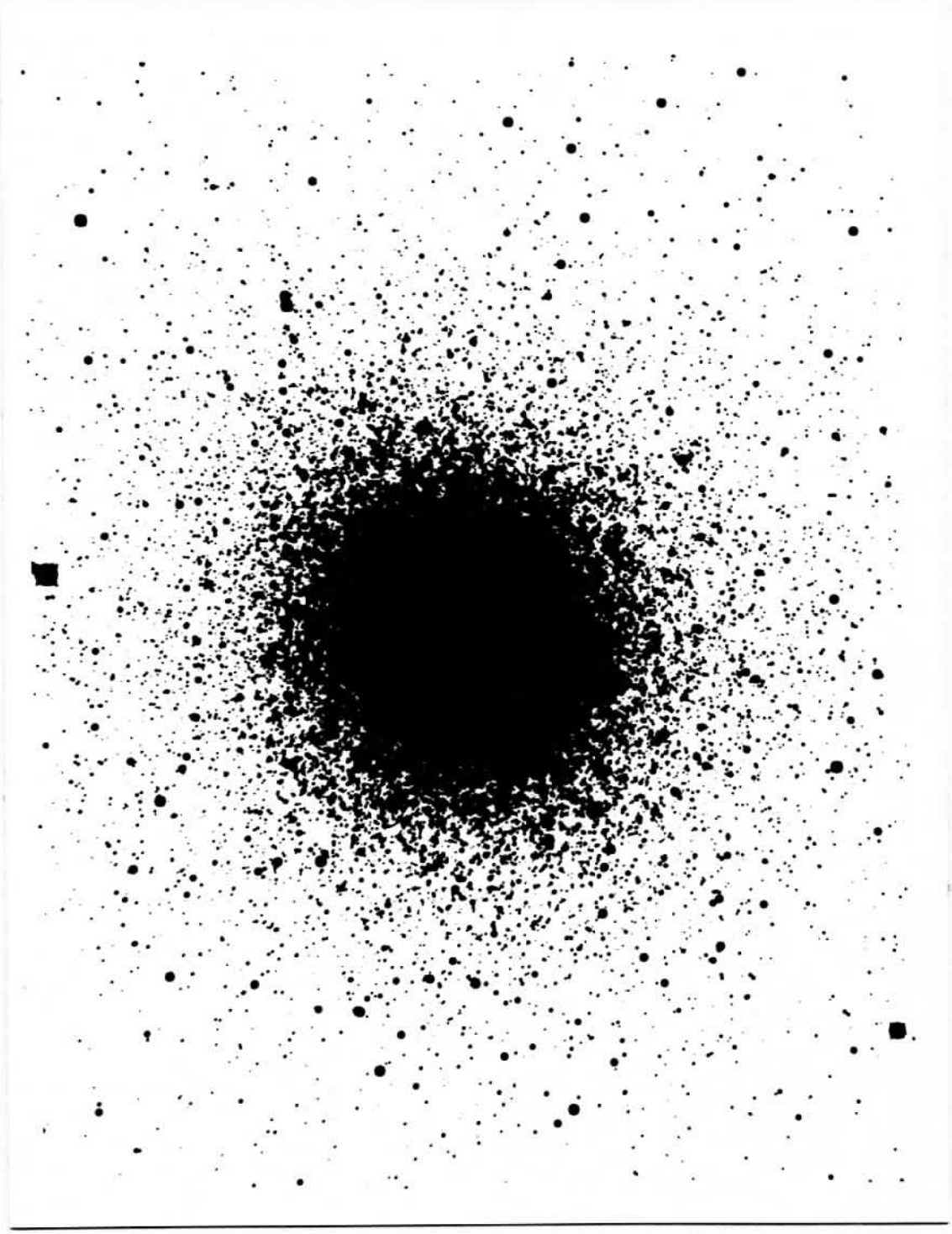
(Astronomy)

at the

UNIVERSITY OF WISCONSIN-MADISON

1979



Frontispiece: The globular cluster Messier 92.
(Photo courtesy of the Kitt Peak National Observatory.)

A DIFFERENTIAL POPULATION SYNTHESIS APPROACH TO MASS SEGREGATION IN M92

William John Tobin

Under the supervision of Assistant Professor Kenneth H. Nordsieck

ABSTRACT

Spectra obtained with the Wisconsin intensified Reticon scanner are presented of 26 low-metal stars and of the center and one-quarter intensity positions of M92. Spectral coverage is from 390 to 870 nm with resolution better than 1 nm in the blue and 2 nm in the red. Individual pixel signal-to-noise is about 100. Dwarf features are notably absent from the M92 spectra. Numerical estimates of 36 absorption features are extracted from every spectrum, as are two continuum indices. Mathematical models are constructed describing each feature's dependence on stellar color, luminosity, and metal content and then used to estimate the metal content of 6 of the stars for which the metal content is not known.

For 10 features reliably measured in M92's center and edge a mass segregation sensitivity parameter is derived from each feature's deduced luminosity-dependence. The ratio of feature equivalent widths at cluster edge and center are compared to this sensitivity: no convincing evidence of mass segregation is seen. The only possible edge-to-center difference seen is in the Mg b 517.4 nm feature. For this feature Christensen's (1972) M92 population synthesis and

Da Costa and Freeman's (1976) M3 mass segregation model are used to estimate crudely the expected center-to-edge change. If the observed difference is real it is much larger than the calculated change, and this is discussed. Three of the 10 cluster features can be of interstellar origin, at least in part; in particular the luminosity-sensitive Na D line cannot be used as a segregation indicator.

The experience gained in this thesis suggests that an integrated spectrum approach to globular cluster mass segregation is very difficult.

An appendix describes in detail the capabilities of the Pine Bluff Observatory .91 m telescope, Cassegrain grating spectrograph and intensified Reticon dual diode-array detector. It is possible to determine a highly consistent wavelength calibration. Pixel-to-pixel gain variations (primarily due to image-tube irregularities) may be removed to $\frac{1}{4}$ - 1%, depending on circumstances. A flux calibration curve may be determined to 5%. The decay of the image-intensifier phosphor is slow and illumination dependent, and prevents observation of faint objects immediately following bright ones.

In the appendix the author draws on his experience gained in this project to advise future observers about observing technique. Various details of the reduction procedure are also considered.

A foreword, written for friends and relatives, may be of anecdotal interest now, and historical interest a century hence.

Kenneth H Nordsieck

Dedicated to taxpayers everywhere

ACKNOWLEDGEMENT

Many people gave me the emotional, spiritual, intellectual and financial help necessary to produce this thesis, and to them, thanks. But I am especially appreciative of the aid rendered by:

1) Ken Nordsieck, my advisor, who came out to Pine Bluff far more than I would have done for a student of mine.

2) Don Michalski who, besides designing the Reticon electronics, cheerfully, efficiently and rapidly mended the many pieces of equipment which seemed especially prone to failure when I was using them.

To these two men, $(\text{thanks})^2$.

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FOREWORD FOR FRIENDS AND RELATIVES

The State of Wisconsin was the thirtieth to enter the Union, in 1948. Situated in the north-central US, it is bounded on three sides by natural barriers: to the west by the Mississippi and St. Croix rivers, to the east by Lake Michigan and to the north by Lake Superior and the detached Upper Peninsula of Michigan. In the last ice-age glaciers covered all but the southwestern portion of the state. When the ice-sheets retreated they left behind gently rolling countryside and nearly ten thousand lakes. Originally mostly forested, Wisconsin is now heavily agricultural, famed (not only on its automobile license plates) for its dairy products, but also producing corn, hay, oats, potatoes, soybeans, peas, tobacco, cranberries, beef, hogs and chickens. Manufacturing is important, especially in the towns of the Rock and Fox river valleys and along Lake Michigan's shore. Mining and quarrying once flourished: Wisconsin is nicknamed "the Badger State" after the early lead miners who, like badgers, spent much time underground. The lush greenery, the lakes and the climate make Wisconsin a vacationground in the summer, and tourism is an important activity in the state.

Wisconsin's capital is Madison, pinched between the Four Lakes (Mendota, Monona, Wingra and Waubesa) of the Yahara River. Madison is a splendid place and it was to the University of Wisconsin-Madison that I came late in 1975, primarily because, at that time, there was no application fee for the graduate school. Madison offers many diversions: the lakes, a score of parks, bars and bistros, an open air market, some theater, music, galleries, a handful of buildings

by Frank Lloyd Wright, the interminable wranglings of the City Council, more potholes than I would have believed possible on University Avenue, movies in abundance, and, of course, people.

What people! Healthy, well-fed, strong and sturdy, many blonde and blue-eyed, bronzed by the sun in the summer. (It's not quite true that there are only two seasons in Wisconsin, July and winter.) People from all over the United States, people from all over the world. Gays and straights. Liberals and conservatives. Pot heads and tee-totallers. A distressing number who believe in God. The fun-loving and the serious.

However, in as much as I ever have a serious intent, I arrived in Mad City with a serious ambition - the pursuit (and with this document, the capture) of a Ph.D. in astrophysics. This introduction describes in simple language for the benefit of friends and relatives what I have been doing these last four years in exile.

The Department of Astronomy in Madison has its origins in the Washburn Observatory, founded in 1878 by the then governor of Wisconsin, Cadwallader C. Washburn. The department no longer occupies the observatory's original attractive sandstone building on Observatory Hill overlooking Lake Mendota (figure F.1). Madison astronomy now haunts the top floors* of the extension to Sterling

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* Astronomy departments seem always to occupy the top floors of buildings - to be closer to the stars?

Figure F.1: The original Washburn Observatory on Observatory Hill, immortalized by the Irving Berlin song, "When it's dark on Observatory Hill."

Hall, a structure that was blasted to national fame when it was bombed in the early hours of 1970 August 24 in a Vietnam-era protest.

The structure of graduate education in the US is rather different from what it is in the UK. For my first two years in Madison I sat in class and attempts were made to teach me some astronomy and a little physics. Apart from two summers elsewhere (one in Virginia, one in New Mexico) I did little research. Ending the coursework there was a comprehensive examination ("prelims") after which I was permitted to proceed with Ph.D. research.

That was two and a half years ago. Before I continue let me digress about spectroscopy, a technique very important to astronomers. Much of what man has learned about the cosmos comes from studying the spectra of the various luminous objects in the universe. What is a spectrum? A musical analogy is to consider a pianist playing a chord. Only certain strings in the piano are vibrating: only certain notes are sounding. The chord is a combination of different notes. A sound spectrum would break down the chord into its component notes and specify which strings were sounding. In a light spectrum the light from some source is split into its component colors. For instance, the red-orange-yellow-green-blue-purple of the rainbow or of sunlight passed through a prism are both crude spectra. More snazzily, a spectrum may be presented as a graph or a table of numbers recording how much power there is at particular colors. Figure 1 of the main section of this thesis displays many spectra graphically. The horizontal axis, "wavelength", is, crudely speaking, the color of the light and the vertical axis, "log F_ν", is how much power is present. You will notice that there is a general systematic variation of flux with wavelength (it may become larger or smaller at longer wavelengths); in addition over certain small wavelength intervals the flux may drop sharply in what is called an *absorption line*. From a study of the spectra of luminous objects much can be unravelled about the objects themselves, their physics and the nature of any material dispersed between them and us.

To produce a spectrum experimentally three devices are necessary. First, a telescope with a big lens or mirror to collect a lot of light (astronomers are only rarely interested in magnification). At the UW's Pine Bluff Observatory 25 km west of Madison I used a .91 meter reflecting telescope - a telescope in which the light is collected by a mirror .91 meter in diameter. The telescope optics and drive were refurbished in 1978. This work resulted in crisper images and telescope gears which do not seize up in winter.

Second, a spectrograph is required: a device to fan the light into its constituent colors - a prism, say. At Pine Bluff the Boller & Chivens Grating Spectrograph that I used had problems and turned out to be the weakest link in the observing set-up.

Third, some means is needed of recording the spectrum produced by the spectrograph. Traditionally this has been film. Film, however, is very inefficient: typically only one one-thousandth of the light falling on film causes blackening in the negative and to achieve a good negative long exposures are necessary. In 1977 the Space Astronomy Laboratory's Don Michalski and my advisor, Ken Nordsieck, were finishing the construction of an "image-intensified Reticon diode-array detector", a detector that is nearly 10% efficient. This meant I could contemplate in two years a project that otherwise would have taken two hundred!

A Reticon chip is another of Silicon Valley's miracles. Figure F.2 shows the Reticon chip at Pine Bluff. Reticons were

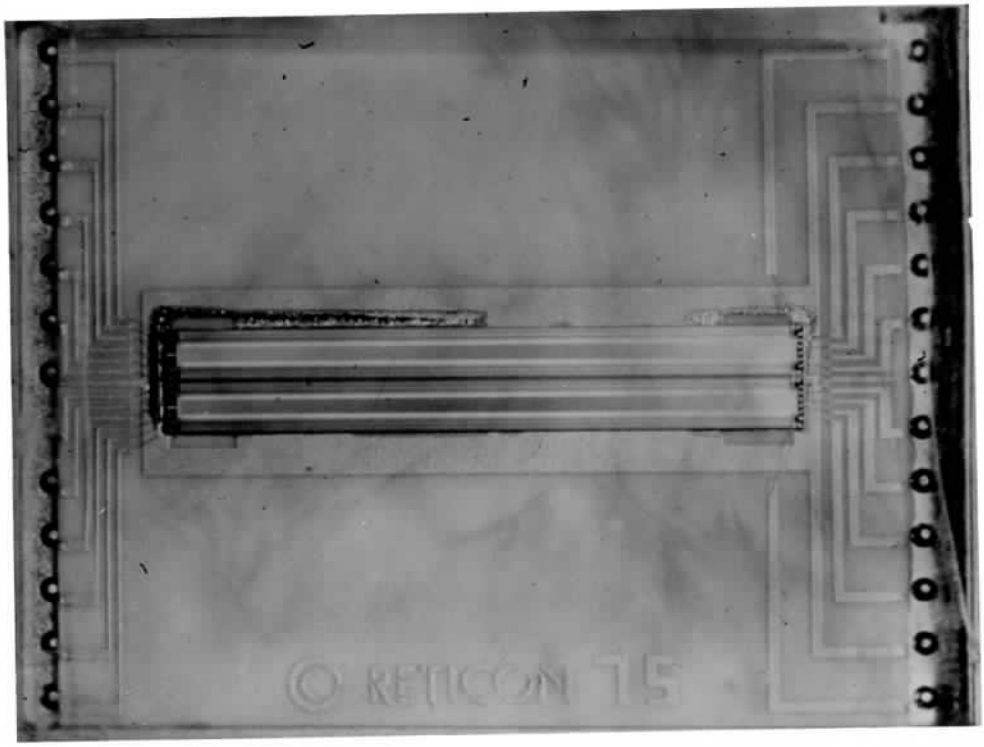

Figure F.2: The Reticon chip. The two horizontal bars each contain 1872 light-sensitive diodes. Connecting wires can be seen to the left and right. The whole chip is 30 mm long.

developed for supermarket check-outs clever enough to read the Universal Product Code pattern of bars now found in North America on most merchandise - from Coca-Cola to contraceptives. In a Reticon's silicon base there has been diffused-in a line of nearly two thousand tiny* *photodiodes*, light-sensitive electronic components. In operation, each photodiode has a voltage applied to fill the diode with charge. The voltage is removed, and light falling on the

* three-fourths by one sixtieth of a millimeter.

photodiode causes some of the charge to escape. After a time each diode can be examined to ascertain how much charge has been lost. The quantity missing is an indication of how much light fell on the diode, and so the diode acts as a sensor. For an analogy, consider a sheep-dip! Initially the trench is filled with disinfectant. Every time a sheep is propelled through the dip, the animal takes away some disinfectant as it leaves. By seeing how much disinfectant has been lost after a time, it is possible to estimate how many sheep have been dipped and the trench acts as a counter.

The line of the fanned-out spectrum from the spectrograph is fed to the line of Reticon photodiodes so the whole spectrum can be recorded simultaneously. (Two thousand sheep-dips side by side.) The charging and examining of the photodiodes is all under computer control. At the observatory the charge lost is recorded on a computer cassette tape, ready for later analysis in Madison.

Figure F.3 shows the Pine Bluff mirror cell, spectrograph and Reticon detector.

The problem I have addressed in this thesis concerns *globular clusters*. Our own galaxy, the Milky Way, is a flattened disk of stars, gas and dust, bulging at its center, mildly reminiscent of a fried egg on a mirror. A cloud of globular clusters haloes the Milky Way; some 200 are known. Each globular cluster is a congeries of between one hundred thousand and one million stars. The stars are bound together by their mutual gravitational attraction into a ball. The frontispiece is a picture of one globular cluster, M92,

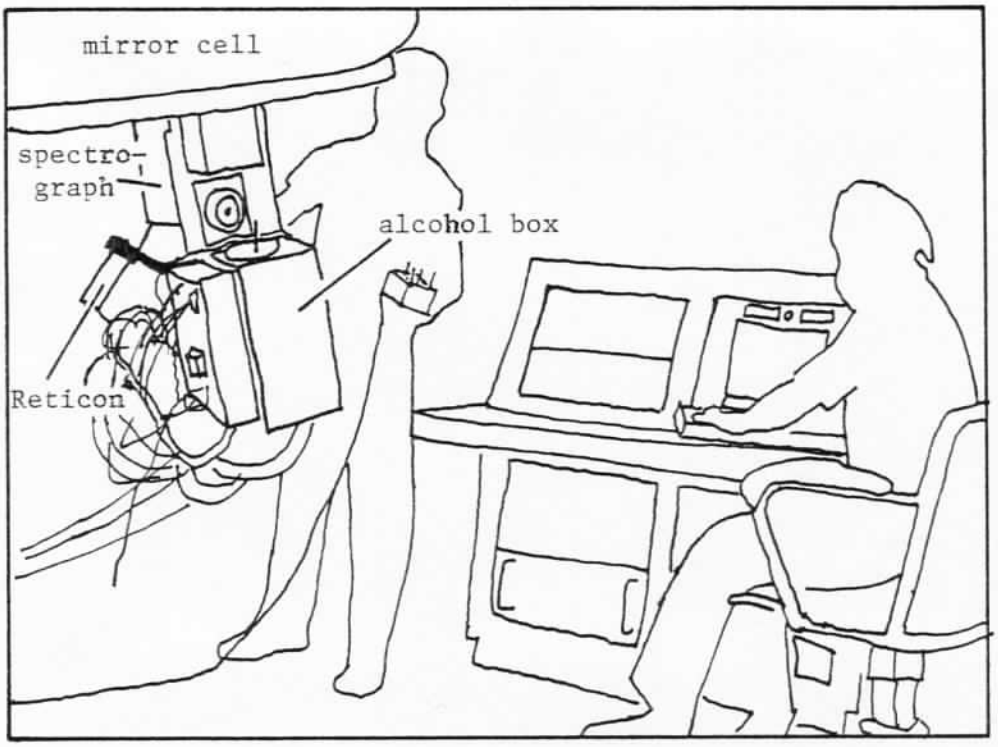

Figure F.3: The dome observing equipment at Pine

Bluff Observatory. Just above my head is the telescope mirror cell. The spectrograph is bolted to the cell's underside and is painted white. The silvery box contains alcohol (for cooling the Reticon, not warming the observer). The Reticon is in the brushed aluminum cube about 200 mm on a side and attached to the spectrograph by a stubby tube. The man with the beard is Ken Nordsieck. He is sitting at the control panel, pretending to type instructions to the Reticon-controlling computer.

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the one I elected to observe. M92 contains about 200 000 stars.

It is hypothesized that as the (rather large) cloud of matter that became the Milky Way was collapsing and flattening, globular clusters condensed out: this explains their unflattened flight around the flattened Milky Way. It also means the clusters are very old - they have been around for a long time. Indeed, globular clusters are almost as old as the universe itself.

Their great antiquity suggests that they may have reached a serenity of age technically known as *relaxed*. What primarily makes one star different from another - and determines its evolution and ultimate death - is its *mass*, the amount of material in the star. If M92 is relaxed, the more massive stars should preferentially be near the cluster center; lighter stars should swarm to the outer reaches. (When the cluster formed the stars were all jumbled together. It is only with time's passing that the cluster's gravitational field sorts the stars.)

This *mass segregation* has not been convincingly confirmed observationally. I hoped that by using a novel technique ("population

synthesis") and the Reticon detector I would have a better chance of identifying any mass segregation that there might be in M92.

What is population synthesis? Any spectrograph has an entrance hole down which the light to be analyzed must pass. Normally a single star's light is passed into the spectrograph, but with an object like a globular cluster several thousands of stars' light fills the entrance opening. The spectrum produced is then just the sum of the several thousand spectra of the individual stars. In the musical analogy, it is as if several thousand pianists were playing at once. If it is known what the (different) spectra of the different classes of stars present in the cluster are it is possible mathematically (using techniques of operations research) to undo the sum, to go back to individual groups of pianists playing different chords. It is possible to say the cluster is composed of x% of stars of this type, y% of stars of that type, etc. This is the technique of population synthesis and has been applied several times to perform stellar censuses of galaxies. By taking spectra at different locations within a globular cluster - at the center and further out - I hoped to see the percentages x, y, etc. change, and change in a way that could be interpreted as a separation of the heavy stars from the light.

The plan was simple: observe examples of all the different types of stars believed to be in M92; observe M92's center and edge; perform the population synthesis; see a difference in the populations; publish the results; gain fame.

The first problem was choosing examples of stars that I believed to be representative of those in M92. These individual stars cannot be stars in M92: M92 is too distant, and consequently the stars too faint to observe individually with the equipment at Pine Bluff. It's necessary to choose stars that are reasonably close to the solar system so that they are bright enough to observe in isolation. (With the cluster the light of several thousand stars together is being observed, and there is no faintness problem.) Most stars near the sun, however, are the stars of the disk of the Milky Way, stars that are greater by a factor of about 200 in a quantity known as *metallicity*. Astronomers are notorious (and deserve to be censured severely) for their misuse of terms: for example, the form of hydrogen that astronomers call HII all other scientists call HI. To an astronomer, any element that is neither hydrogen nor helium is a "metal" - so the earth's atmosphere, for instance, is principally composed of the well-known "metals" nitrogen, oxygen and argon. We all have hearts of steel!

Metals are produced by the nuclear fusion that keeps a star shining and also in the death throes of massive stars.* When a star dies some of these metals may be spewed back into space, contaminating the interstellar gas that will condense to form later generations of stars. In this way, as the universe has got older its metal content has increased. Very old stars (such as those in M92) have a

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* Since we are mostly metals, we are truly star-children.

very low metallicity because their genesis was at a time when there were not many metals around. Metal production is now believed to be tapering off and younger stars - those of the galactic disk - all have about the same metallicity, 2%. Consequently, population syntheses of spiral galaxies have been reasonably successful: there are lots of easily-observable stars and it's only necessary for a population synthesis to have a grid of stars of different masses and evolutionary epochs (or, equivalently, different luminosities and surface temperatures. The metal content, luminosity and surface temperature completely determine the spectrum of a star.) It was not possible to find enough .01% metal stars to observe a decent sample for M92's synthesis: I had to be satisfied with stars of reduced metal content, but not by the requisite amount.

However, when it came down to brass tacks, I adopted an analysis rather simpler than a full population synthesis, an analysis that neatly solves the problem of the metal content. But before I dive into that let me detail the nuts-and-bolts of observing - how I actually made my observations.

It was not enough to know that I wanted to look at a star such as HD 161716 or BD $+39^{\circ}4926$. It was necessary to be able to find it in the sky! Typically, my stars were fainter than can be seen with the naked eye. For each star I prepared a finding chart - a card with the star's name, coördinates in the sky, a map traced from a star atlas, and, most importantly, a copy of the Palomar Sky Survey photograph of the sky in the vicinity of the target star. At the

observatory it is possible to aim the telescope pretty closely using coördinates, but it is only by recognizing the pattern of the neighboring stars that one can be certain the correct star is found.*

Then one has to be assigned telescope time. I was treated very generously and for a year was allocated about one third of the nights. The weather was the next hurdle - would it be clear? I became an avid listener to the National Weather Service's radio station, WXJ87. But I found the most useful and reliable forecasts came from one of Madison's TV stations, WISC-TV, and its bizzare, be-hatted forecaster, Marv Holewinski.

An anticipated night at the observatory necessitated an early dinner, 5.30 - 6.00 in the summer, even earlier in the winter. The 30 km drive to Pine Bluff usually took about 30 minutes and I derived much pleasure watching the seasons change in the verges and fields.

An immediate chore at the observatory was to cool the Reticon detector to near $-32^{o}C$ with dry ice and alcohol. This is because if cooled there is less "noise" in the detector and it is substantially easier to see a signal poke out against the background. (It's much easier to listen to a radio program if the set is well tuned so there is a minimum of distracting hiss and static.) My next tasks would be to turn on all the electronics - the telescope control; the clocks; the computer; the Reticon electronics, display and controller and check that everything was working. Then for the rest

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* Nevertheless, I did misidentify one star.

of the one or two hours (winter/summer) it took to cool the Reticon I could sit quietly and contemplate the sunset or plan the sequence of the night's work.

At sunset the sky was too bright to begin observations but I would begin various calibrations so that as soon as the sky would be dark enough I could begin observing stars. Calibrations were made by "observing" various lamps mounted on the telescope. One calibration was to give a wavelength scale to the Reticon - to determine what color corresponds to which photodiode. Another calibration corrected for diode-to-diode gain variations: a given amount of light does not cause every photodiode to lose the same amount of charge. As soon as the sky was dark enough a *standard star* (one whose flux has already been determined) was observed to derive a correction for light losses in the telescope and spectrograph. (This is only approximately true, but the purpose of observing the standard star is too complicated to go into.) Light losses are severe: at best only one photon in five hundred that falls on the mirror makes it to the Reticon. This is because in the optical path there are 6 reflections and 12 transmissions and some light is always lost on reflection or transmission.)

After all this I would be ready to observe my program stars and cluster. Because of the long set-up time it made sense to observe right through to dawn (or until clouds rolled in!) and to take no rest-breaks. A hard life.

To observe a program star I had to set on it, first using the Palomar Sky Survey photograph and a small finding telescope strapped to the .91 meter, then using the .91 meter itself. In winter this was an unpleasant task. On the coldest night I observed the temperature inside the dome was -22°C! Even though I was wearing a union suit, thick pants, shirt, a sweater, a snowmobile suit, and a hat and earmuffs, it was plain painful to be at that temperature for very long. Luckily before the 1978/79 winter a closed-circuit television system had been added to the spectrograph and once a star had been found, fine adjustments to the telescope tracking (to keep

Figure F.4: Down in the basement. I am surrounded by computer equipment. One of the TVs is for guiding. In my hands are finding cards.

starlight going through the spectrograph entrance slit) could be made using a TV monitor in the observatory's heated basement. It was necessary to check the tracking continuously. Consequently I was always occupied, rather monotonously, right from the time I began observations through to their end near dawn. Music from a cassette playing or WLVE stereo, and sandwiches and coffee helped alleviate the boredom. Figure F.4 shows me at work.

When I finished observing I would repeat all the calibrations to check their consistency with those at the night's beginning. I would then go to bed in the observatory's dormitory, exhausted, but not usually able to sleep because the tensions of observing were still with me.* After fitful rest I would breakfast, perform one or two little technicalities and drive back to Madison, usually arriving back about 2 pm, some twenty hours after leaving.

I have described a night in which everything went well and the scheme that had evolved after several months' experience. Infact, especially at the beginning of this project, there were many instrumental and organizational failures. This was expected: any new equipment of the sophistication of the Reticon has a break-in period during which unanticipated problems and flakey electronics show up. I was paid by Ken Nordsieck's National Science Foundation grant partly to find these problems. But there were many more of them than we had ever anticipated. Both Ken and Don came out at night to

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* A bottle of Old Potosi beer usually helped.

service the equipment far more often and with much greater grace than I would have done. In addition, the weather was very bad, and it was all very dispiriting. Table F.1 summarizes the frustration of it all.

Table F.1. The Agony 1978 July 10 - 1979 July 2

(i)	Number of nights assigned	109
(ii)	Number of times I went out to PBO	68
(iii)	No useful observations because of weather	16
(iv)	No useful observations because of instrument failure	9*
(v)	Had to stop early because of weather	5
(vi)	Number of nights on which I took observations which are actually used in this thesis	34
(vii)	(vi) / (i)	31%
(viii)	(vi) / (ii)	50%

* There were more nights when instrument problems did not prevent observations.

Luckily, I had a mental-health break once a month: I was never assigned telescope time near the full moon. For a week each month my life was not ruled by the vagaries of Wisconsin's weather: I could make dates, I could go out drinking, I could sleep nights.

I learned some things observing which I had not expected to. I learned about cars and their dreadful expense. The car the Astronomy Department would arrange was unsatisfactory in several ways and I purchased a gold and rust* colored 1971 Opel. Excluding the cost of the car, the running cost for the first year I ran the Opel was 18¢/km. A trip to the observatory cost $10; at this rate the 3600 km I drove for this thesis totalled $630. That would have bought a lot of hot dinners!

I learned that the trick to starting a car in very cold weather is to remove the battery overnight. I learned never to drive on glare ice when alone at the observatory. I suffered the indignity of having my car towed away to give a clear passage to the very same snow plow crew which had failed to plow out the observatory drive and had caused me to park in the road in the first place. When throwing drunks and intruders off the observatory grounds I learned to be polite and tactful, so they wouldn't come back and bloody my nose - or use a bullet: the United States is a land without gun control. I learned the sound of the whippoorwill and that mosquitoes will find the smallest area of exposed or tightly-covered flesh.

Figure F.5 shows the raw and chilly Modcomp room in Madison. The grey, windowless walls, the noise, and the air-conditioning make it an uncomfortable place to be. I had to spend too much time there. A

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* Real rust. Maybe the car is better described as lemon rather than gold?

lot of computing was required to convert the charges recorded at PBO on computer cassette tapes into the spectra of figure 1. Figure F.6 summarizes the procedure (should you be curious), illustrating the steps for 250 of the two thousand photodiodes.

At the end of July this year I had produced figure 1's spectra. To procure them I had detected 60 billion photons - the individual corpuscles of light. Twenty billion came from objects in the sky, the other 40 billion were from calibrations. The total energy in these photons was about 20 nanojoule. That's enough to run a flashlight for about one ten-millionth of a second. Is it enough to

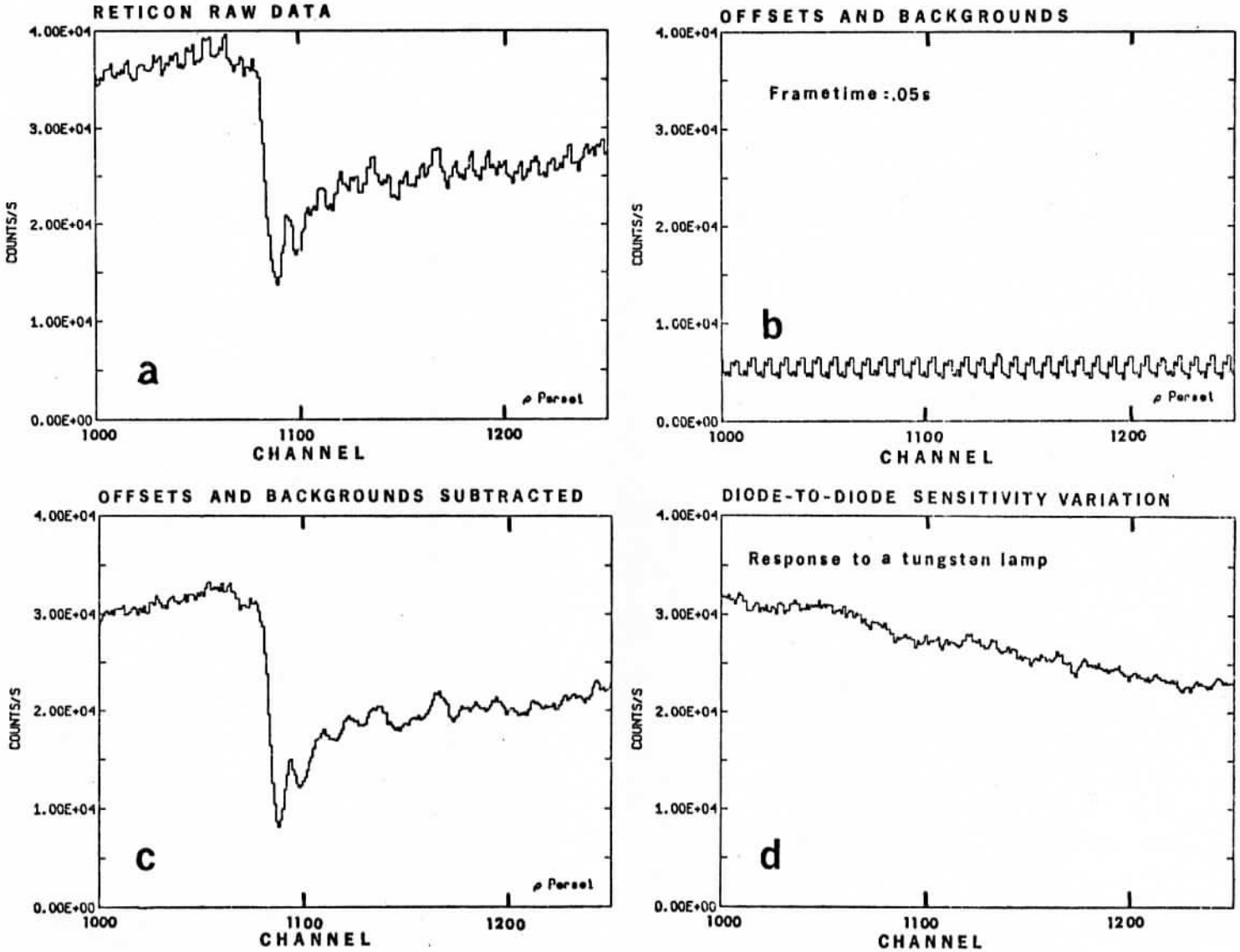
Figure F.5. The bleak Modcomp room.

Figure F.6. The Reticon Reduction Routine.
Pane (a) shows a raw data scan taken of the star ρ Persei. After setting the telescope on a star I would always move to a nearby, empty field and take another scan. (b) shows such a scan. The pattern which repeats every 8 channels (diodes) is one of electronic offsets in the amplifiers that sample the charge remaining in each diode. In this example there is no obvious signal from the sky. (b) is subtracted from (a) to give (c) because (b) does not in any way correspond to "real light". Infact, the level of the electronic offsets can be altered with a knob.

Earlier in the night I had "observed" a tungsten-filament incandescent lamp. Its signal is shown in (d). The spectrum of the incandescent lamp is smooth. Between the spectrograph and the Reticon there is an image-intensifier tube to amplify the spectrum (make it brighter) before passing it onto the Reticon. The jitters in (d) reflect variations in the intensifier amplication. *Dividing* (c) by the signal (d) removes the amplification irregularities. (Amplification is a *multiplicative* quantity.) (e) shows the signal from ρ Persei after the division. Earlier in the night I had also "observed" the line emission spectrum of a mercury and argon gas-discharge lamp. This lamp only emits at certain well-defined wavelengths. (f) shows the lamp's spectrum and then it is possible to assign each channel its appropriate wavelength. Air is not perfectly transparent and a correction is also made for absorption of starlight by the terrestrial atmosphere. This takes us to (g).

Standard stars - ones for which we know what spectrum to expect - are observed several times each night. (h) shows the signal from one, HD 15318, after it has gone through the reduction to stage (g) and then been multiplied up so that the flux from the star corresponds to that which other observers have found (the "Oke points"). The standard star has been used to determine by how much *every* spectrum should be multiplied up to give flux. (This multiplicative function is infact the reciprocal of the spectrum of the incandescent lamp - remember we earlier divided by the incandescent lamp's signal.)

Multiplying (g) by the multiplicative function gives (i) and completes the reduction. Panes (j) and (k) give examples of the spectra of two stars. Mirfak is a star a little hotter than the sun and has a comparatively featureless spectrum. ρ Persei is cool, and its spectrum is heavily eaten away by molecular absorptions in its own atmosphere.


RETICON RAW DATA
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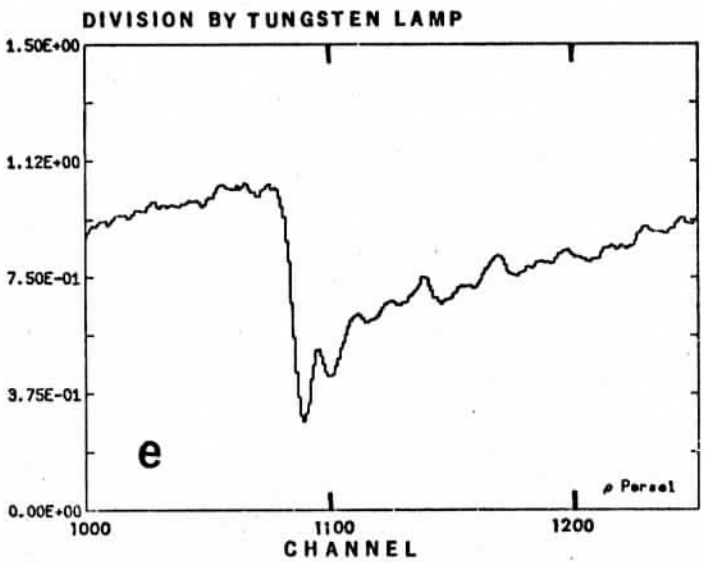
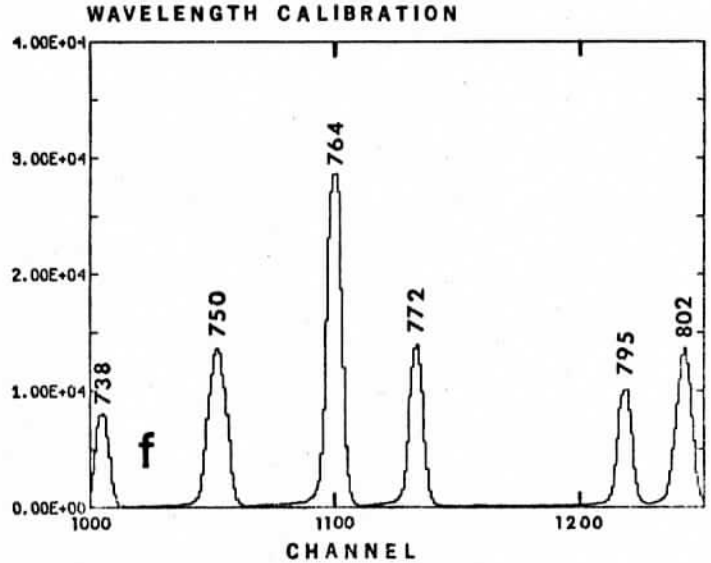
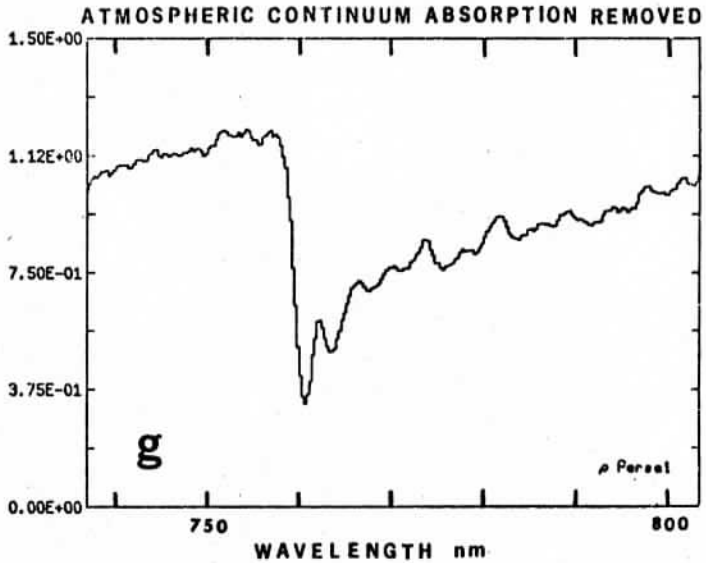
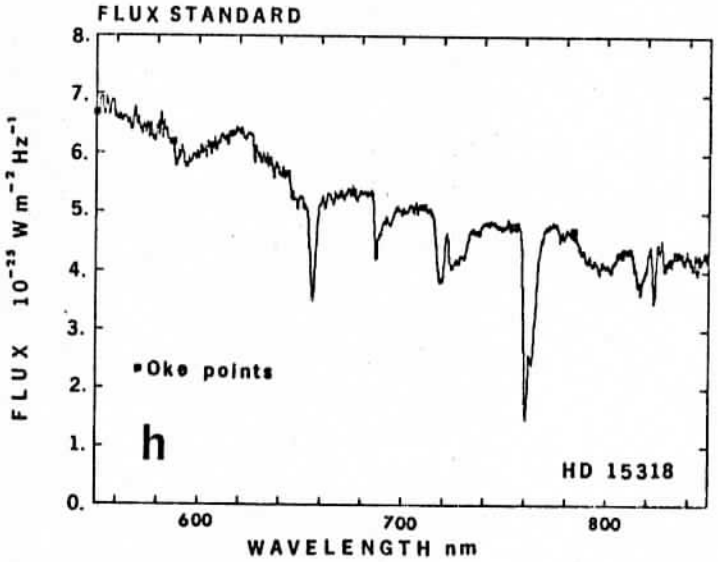
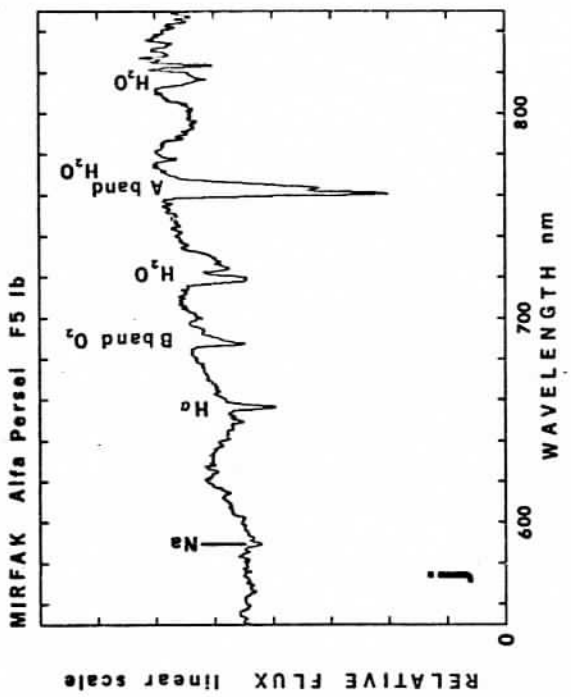
1200
CHANNEL
OFFSETS AND BACKGROUNDS
Frametime:.05s
b
OFFSETS AND BACKGROUNDS SUBTRACTED
c
DIODE-TO-DIODE SENSITIVITY VARIATION
Response to a tungsten lamp
d

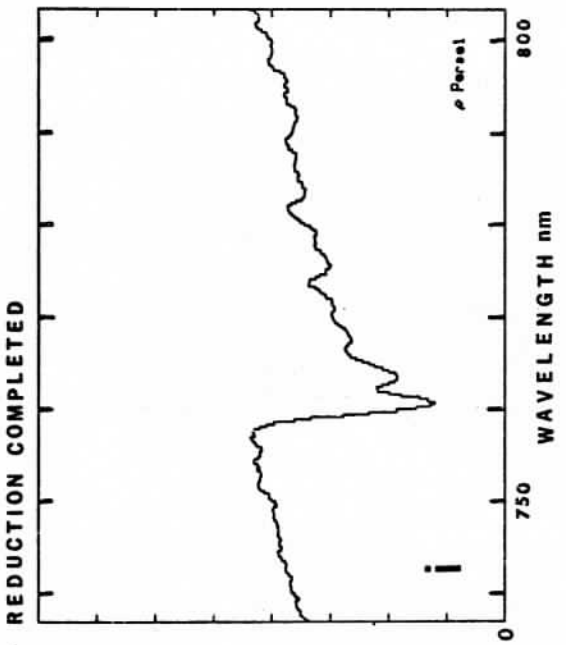

DIVISION BY TUNGSTEN LAMP
1.50E+00
1.12E+00
7.50E-01
3.75E-01
0.00E+00
1000
1100
1200
CHANNEL
e
ρ Persei

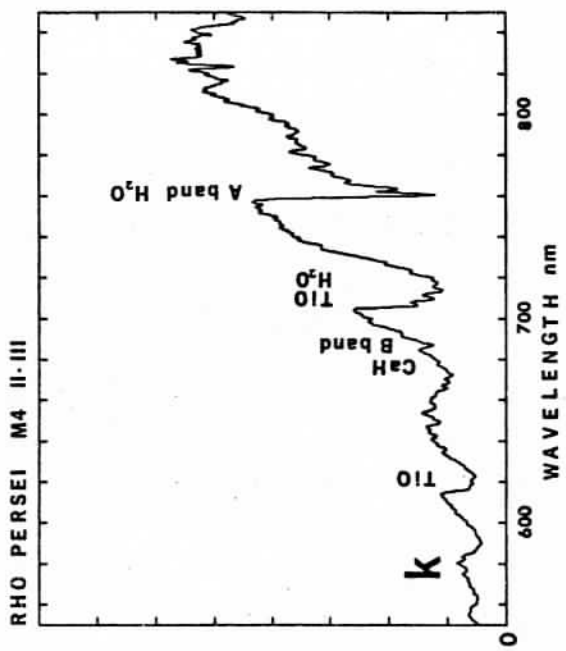

WAVELENGTH CALIBRATION
4.00E+04
3.00E+04
2.00E+04
1.00E+04
0.00E+00
1000
1100
1200
CHANNEL
738
750
764
772
795
802
f


ATMOSPHERIC CONTINUUM ABSORPTION REMOVED
1.50E+00
1.12E+00
7.50E-01
3.75E-01
0.00E+00
750
800
WAVELENGTH nm
g
ρ Persei


FLUX STANDARD
FLUX 10⁻²³ W m⁻² Hz⁻¹
8.
7.
6.
5.
4.
3.
2.
1.
0.
600
700
800
WAVELENGTH nm
•Oke points
h
HD 15318


MIRFAK Alfa Persei F5 Ib
Na
Hα
B band O2
H2O
A band H2O
H2O
j
RELATIVE FLUX linear scale
0
600
700
800
WAVELENGTH nm


REDUCTION COMPLETED
ρ Persei
i
RELATIVE FLUX linear scale
0
750
800
WAVELENGTH nm


RHO PERSEI M4 II-III
A band H2O
TiO
H2O
CaH
B band
TiO
k
RELATIVE FLUX linear scale
0
600
700
800
WAVELENGTH nm

shed any light on globular cluster mass segregation?

Perhaps. Unfortunately my stay in Wisconsin (and the money to support me) ran out, and I was only able to perform the simplest analysis of my spectra. First, I examined the stellar spectra and was able to distinguish about 36 different absorption lines in them. For every star I extracted measures of the 36 features called *equivalent widths*. Stronger lines have larger equivalent widths. The widths swell Table II. I then devised and fitted to the equivalent widths a simple mathematical model. The model describes how a feature's equivalent width varies with stellar temperature, luminosity and metal content.

Voilà! The metal-content problem is solved: the mathematical model tells how strong a particular line would be in stars of M92's metallicity, or indeed, any metal content I care to name. I could then produce a luminosity and temperature grid of synthesis stars of the type in M92, without having observed a single one of the appropriate metal content! I could perform a population synthesis for M92's center and edge and look for differences. But time ran out.

Instead, for the nine lines which I had convincingly detected and measured in M92 I calculated a quantity related to how sensitive each particular feature should be to mass segregation. Figure 5 plots the ratio of M92's center-to-edge equivalent widths against this sensitivity. If there is any mass segregation in M92, the more sensitive lines should show a bigger change from center to edge.

Do you see any trend in figure 5? I don't, though the outlying magnesium (Mg b) and sodium (Na D) points need explanation.

If all this seems like a lot of effort to produce a graph that looks like an ink blot, let me add that a major part of what I did was to investigate the performance of the Reticon and spectrograph. The Appendix reports on the instruments' properties, and overflows with useful information for future observers at Pine Bluff.

That's what *I* did, and pretty much I enjoyed myself. How did *you* spend these last four years?

Table II Equivalent width and continuum indices. Equivalent widths are in picometer.

	393.4		396.8		410.1		420.0		422.7		425.6		427.5	
	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε
M92 CENT	287	3	490	69	270	37	-13	11	26	14	-8	8	20	21
M92 46%-	308	35	445	58	297	87	6	3	-7	13	64	27	-2	14
M92 EDGE	219	32	560	3	249	3	1	0	26	44	58	22	-2	1
19445	....	....	....	....	....	....	....	....	....	....	....	....	....	....
25329	915	102	764	47	117	54	76	38	168	22	57	3	83	1
46703	433	138	608	90	280	18	17	34	20	30	-19	37	13	12
64090	711	9	546	49	90	7	12	5	65	1	21	4	20	5
74462	780	53	627	15	68	62	-20	47	65	6	18	23	17	8
81192	809	11	727	17	68	47	56	9	120	13	48	7	40	9
84937	177	83	499	39	333	34	-9	8	-1	5	-6	7	-3	5
+32 2188	5	38	370	123	362	32	2	26	53	3	4	30	13	6
103095	892	2	668	113	42	55	73	46	156	9	44	22	55	27
+52 1601	640	41	558	45	18	49	34	46	49	13	4	63	4	12
105546	679	33	488	39	98	22	37	60	16	45	7	3	6	3
114762	666	40	565	56	214	2	26	16	46	17	21	9	24	6
122563	458	5	396	8	77	4	16	8	2	15	33	9	1	4
124897	649	17	669	21	141	15	113	3	168	15	100	2	70	1
132142	838	203	641	70	105	8	91	11	167	9	94	14	84	10
+30 2611	512	609	483	184	97	57	81	30	54	0	49	2	16	2
140283	229	15	422	31	219	55	-4	12	5	11	28	9	24	7
161817	41	34	854	49	681	59	-7	6	3	6	39	5	28	3
165195	452	2	336	68	59	16	-7	34	15	29	40	17	17	6
170737	778	17	592	21	46	40	72	6	89	8	40	34	50	24
180617A	....	....	....	....	....	....	....	....	....	....	....	....	....	....
182939	366	15	554	10	308	21	14	6	30	7	12	6	21	7
232078	75	55	141	43	85	27	15	20	65	37	67	19	54	31
201891	537	17	557	27	237	43	0	4	46	15	1	10	21	14
+39 4926	49	24	726	93	579	5	-14	13	1	7	4	4	-10	1
221170	626	42	541	28	58	19	39	9	29	4	18	12	16	6

	430.1		432.6		434.0		435.7		438.5		440.9		446.2	
	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε
M92 CENT	145	19	-24	1	196	33	-45	2	5	15	6	19	6	13
M92 46%-	82	53	-17	6	240	13	-29	4	31	25	-4	25	15	29
M92 EDGE	127	7	-9	2	216	19	-42	34	28	49	14	11	2	6
19445	....	....	....	....	....	....	....	....	....	....	....	....	....	....
25329	617	32	2	8	-26	5	3	6	260	3	134	1	61	7
46703	206	37	-38	4	312	18	-38	3	105	4	82	3	13	3
64090	469	1	13	5	64	20	-9	6	113	9	50	9	34	15
74462	669	0	11	14	-23	8	16	0	197	38	100	6	117	7
81192	701	16	30	14	-13	20	23	2	306	17	123	13	120	15
84937	-93	24	-32	6	319	25	-14	25	-14	14	-10	8	17	2
+32 2188	-33	29	-26	8	377	35	-49	24	31	82	-32	16	-4	28
103095	496	37	43	21	-22	1	23	5	235	3	94	27	113	1
+52 1601	614	76	16	9	37	57	-4	15	175	55	75	1	66	6
105546	375	43	4	8	119	14	42	11	117	38	51	6	59	12
114762	408	3	-7	7	181	6	-7	1	112	5	64	3	40	7
122563	287	23	-8	9	72	3	6	5	72	7	31	12	13	5
124897	710	4	66	1	-24	4	30	6	354	5	138	11	211	1
132142	630	24	60	2	33	3	47	6	343	37	159	16	140	18
+30 2611	578	166	28	3	19	68	3	12	229	5	131	35	161	5
140283	84	4	-2	5	180	22	-35	2	28	12	-19	1	29	20
161817	-215	5	-33	4	606	6	-64	24	-54	14	-13	17	-12	44
165195	394	5	-3	8	68	1	-5	11	106	1	38	16	15	9
170737	595	30	55	13	-32	4	-6	2	260	78	130	31	81	21
180617A	....	....	....	....	....	....	....	....	....	....	....	....	....	....
182939	104	21	-20	6	313	9	-65	3	11	18	-4	22	-17	37
232078	463	9	23	16	55	4	-5	3	212	50	111	9	189	23
201891	307	4	15	4	191	6	-22	2	111	13	63	2	61	44
+39 4926	-69	25	-16	8	517	26	-151	16	-4	1	-5	26	-8	3
221170	471	20	-6	7	21	21	-9	10	118	49	35	21	55	3

	453.2		466.7		470.5		476.1		486.1		491.8		494.0	
	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε
M92 CENT	73	48	-0	2	11	10	19	2	407	64	27	2	23	3
M92 46%-	32	7	6	3	26	12	23	31	221	44	56	7	-5	1
M92 EDGE	61	77	6	14	12	2	-18	4	333	51	22	13	-26	0
19445	....	....	....	....	....	....	....	....	....	....	....	....	....	....
25329	135	31	-6	11	29	14	24	18	98	3	45	18	-11	6
46703	54	8	-11	8	-21	26	36	2	434	74	75	12	41	2
64090	51	35	-2	10	4	1	13	16	187	10	14	9	-8	10
74462	210	26	31	32	19	13	58	38	225	29	69	11	53	0
81192	224	17	24	9	54	8	58	11	230	19	69	5	44	12
84937	58	10	1	3	19	14	-21	27	475	9	7	34	14	26
+32 2188	-51	8	15	4	28	4	21	14	515	35	-11	16	-26	16
103095	173	66	2	1	35	29	28	13	125	17	80	15	19	7
+52 1601	189	66	12	3	56	30	42	6	216	40	62	2	34	14
105546	174	37	-3	29	30	5	46	9	161	10	38	9	30	15
114762	166	6	17	2	48	9	32	11	350	4	42	3	24	4
122563	63	39	-5	10	19	1	19	5	102	28	19	11	14	1
124897	356	11	43	13	72	8	75	1	215	30	69	12	51	13
132142	264	9	20	6	87	8	55	17	180	57	92	5	56	12
+30 2611	268	22	24	18	60	14	66	11	128	48	75	14	49	3
140283	26	46	8	16	20	3	9	7	277	36	32	3	17	13
161817	39	39	-3	13	21	9	13	24	1044	27	31	8	-45	8
165195	152	3	22	14	67	6	49	1	140	34	79	28	28	1
170737	171	17	37	37	97	26	68	14	202	60	54	4	35	12
180617A	....	....	....	....	....	....	....	....	....	....	....	....	....	....
182939	-3	32	24	0	22	10	23	12	445	52	17	6	2	10
232078	420	27	16	7	61	14	59	4	287	68	27	2	17	1
201891	94	9	5	23	21	7	29	6	366	35	6	3	-15	7
+39 4926	17	11	-7	9	-10	18	26	59	696	27	1	4	1	16
221170	130	49	-15	11	26	6	17	4	64	2	47	5	20	14

	498.4		504.3		507.6		517.4		517.4		520.8		527.0	
	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε
M92 CENT	23	9	33	20	17	1	111	11	44	14	9	39	14	18
M92 46%-	16	1	56	66	55	18	112	99	....	....	24	5	0	13
M92 EDGE	15	9	35	12	49	0	163	5	66	82	69	19	19	19
19445	....	....	....	....	....	....	....	....	42	23	....	....	....	....
25329	41	6	8	0	86	23	555	29	425	2	131	1	155	34
46703	27	37	67	26	2	23	106	87	75	13	31	13	79	6
64090	43	5	26	4	29	8	262	7	177	7	41	9	65	9
74462	7	6	56	20	92	23	146	58	82	21	12	17	96	22
81192	46	1	45	7	101	14	338	69	269	26	34	25	132	6
84937	-1	12	4	6	16	43	53	22	46	4	-11	55	62	19
+32 2188	-10	37	-14	77	22	17	-108	33	-47	45	-24	6	51	17
103095	-1	25	27	12	39	22	483	54	416	39	129	15	172	8
+52 1601	33	5	54	9	65	36	110	1	118	11	14	29	58	33
105546	19	19	78	12	80	3	149	1	4	12	16	3	68	19
114762	30	8	34	1	60	2	192	5	184	10	19	5	64	1
122563	5	5	12	13	27	14	124	23	31	52	30	16	39	10
124897	40	5	115	7	135	2	411	20	290	8	74	22	157	28
132142	78	6	76	15	110	23	627	38	549	14	97	23	169	12
+30 2611	40	4	73	2	105	21	194	7	134	52	86	9	136	17
140283	-17	7	-28	15	-34	4	80	11	23	45	33	38	11	23
161817	10	1	-3	14	-25	37	112	71	23	22	2	32	73	37
165195	-8	6	56	0	50	16	158	35	94	8	116	47	82	11
170737	49	15	83	17	78	6	291	22	176	18	63	33	117	10
180617A	....	....	....	....	....	....	....	....	1079	6	....	....	....	....
182939	53	2	40	5	20	26	42	15	156	3	1	6	38	15
232078	54	11	107	7	107	16	290	64	193	101	66	15	129	15
201891	63	17	17	12	24	7	224	20	119	44	22	2	39	23
+39 4926	-4	14	-32	4	-56	12	104	12	8	34	-15	1	-19	0
221170	29	21	59	3	14	16	129	4	50	18	10	7	38	10

	527.0		533.3		539.6		558.9		570.7		585.4		589.1	
	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε	EW	ε
M92 CENT	35	12	35	31	-3	14	5	22	36	6	7	3	84	14
M92 46%-	....	....	....	....	....	....	....	....	....	....	....	....	....	....
M92 EDGE	36	2	-4	33	-19	0	12	54	5	5	28	11	90	10
19445	-10	24	46	0	-15	10	-25	40	19	3	2	11	15	17
25329	73	6	66	4	36	15	137	14	19	8	-5	23	188	19
46703	59	7	84	10	44	10	70	19	57	14	6	35	172	18
64090	50	5	45	9	45	6	88	53	21	0	17	5	73	16
74462	-1	14	19	30	-5	8	112	39	75	23	10	29	29	75
81192	141	5	106	3	72	6	145	55	61	14	62	24	174	24
84937	17	9	-15	26	58	18	4	18	9	9	-0	27	105	33
+32 2188	-23	28	21	0	12	2	113	54	17	13	29	4	119	66
103095	96	16	81	2	14	17	185	52	38	14	72	39	185	70
+52 1601	95	21	53	50	6	4	58	2	36	30	56	10	166	18
105546	20	55	26	14	26	22	87	4	46	49	28	31	3	88
114762	120	29	16	2	14	18	116	4	20	14	57	3	140	39
122563	46	5	32	7	33	14	52	15	4	2	-21	39	52	48
124897	163	5	128	14	140	28	140	15	100	10	29	22	185	4
132142	118	58	112	14	93	41	320	22	88	4	43	12	280	46
+30 2611	111	17	65	47	70	44	139	34	61	22	9	4	108	7
140283	5	9	4	2	-12	22	-21	41	85	35	12	17	126	6
161817	19	19	-10	3	-9	16	17	35	19	4	-14	11	55	4
165195	84	10	53	8	71	6	82	93	49	15	11	55	183	30
170737	86	24	34	8	63	26	145	1	71	4	3	7	185	96
180617A	233	4	94	33	-207	5	-86	49	-0	21	145	27	1564	85
182939	46	27	24	22	40	2	-0	64	-0	12	-24	28	104	90
232078	105	13	30	11	116	8	99	64	78	0	17	14	277	54
201891	99	14	38	34	73	28	98	3	13	20	29	22	157	4
+39 4926	13	1	-6	10	21	18	-7	52	25	16	-2	15	221	15
221170	81	1	56	8	8	13	81	34	27	3	25	12	137	5

FIGURE 1 (cont.)

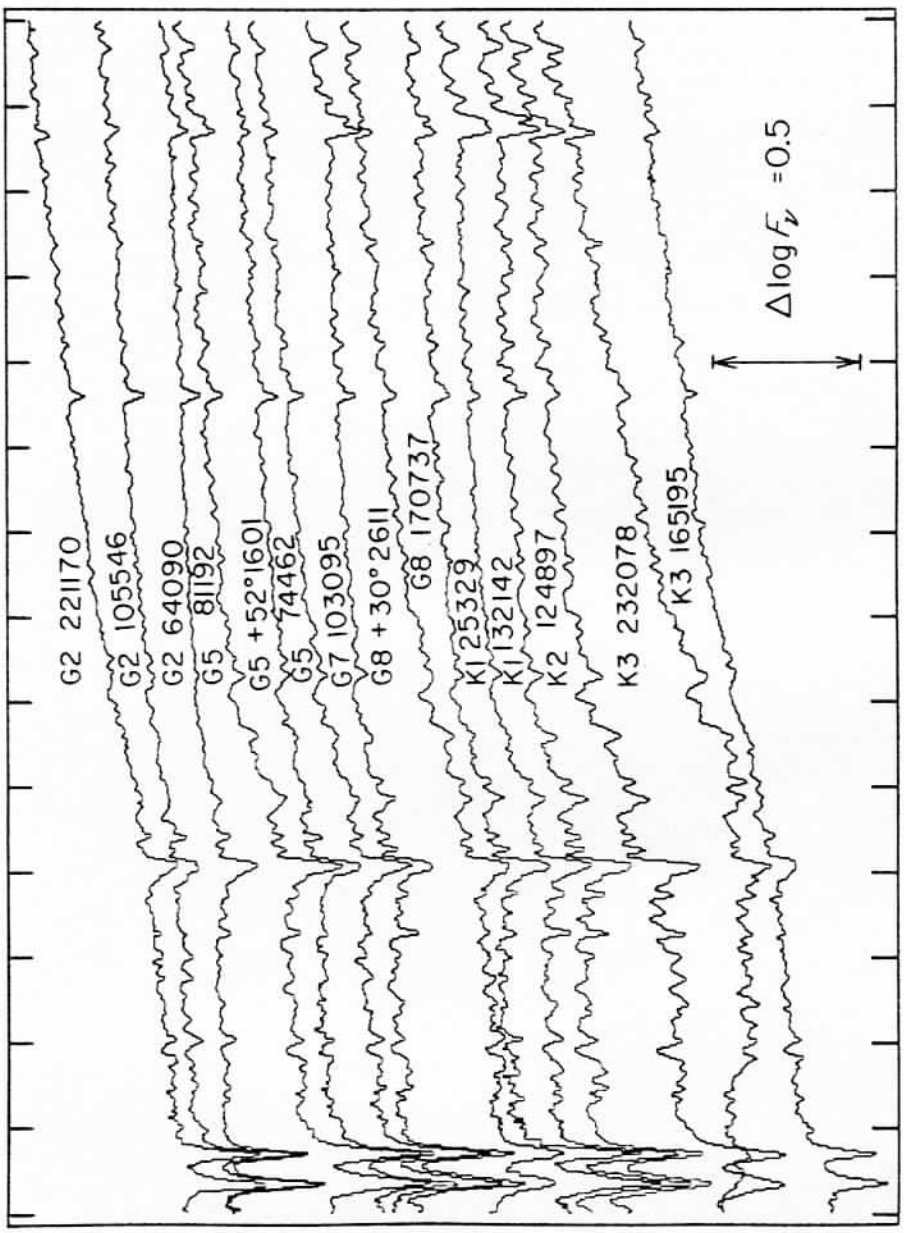


FIGURE 1 (cont.)

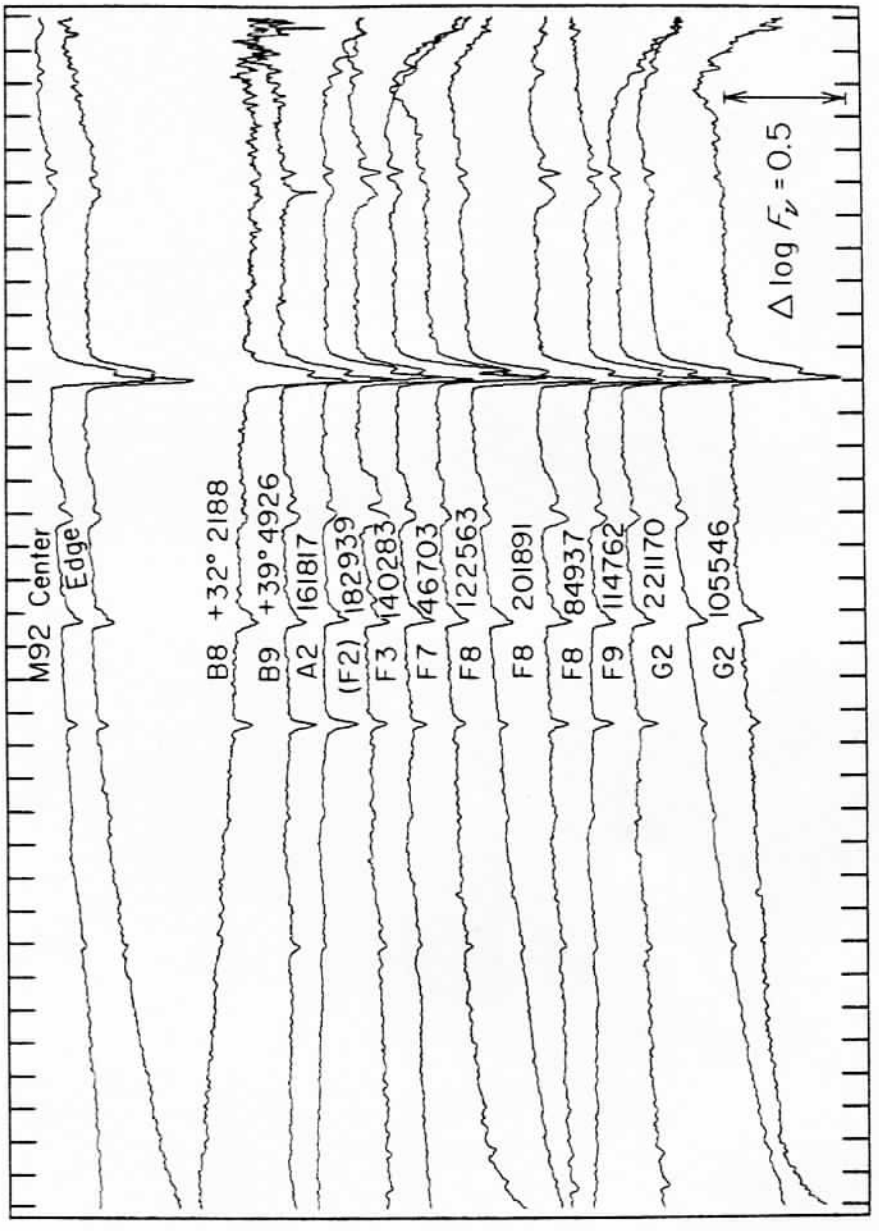


FIGURE 1 (cont.)

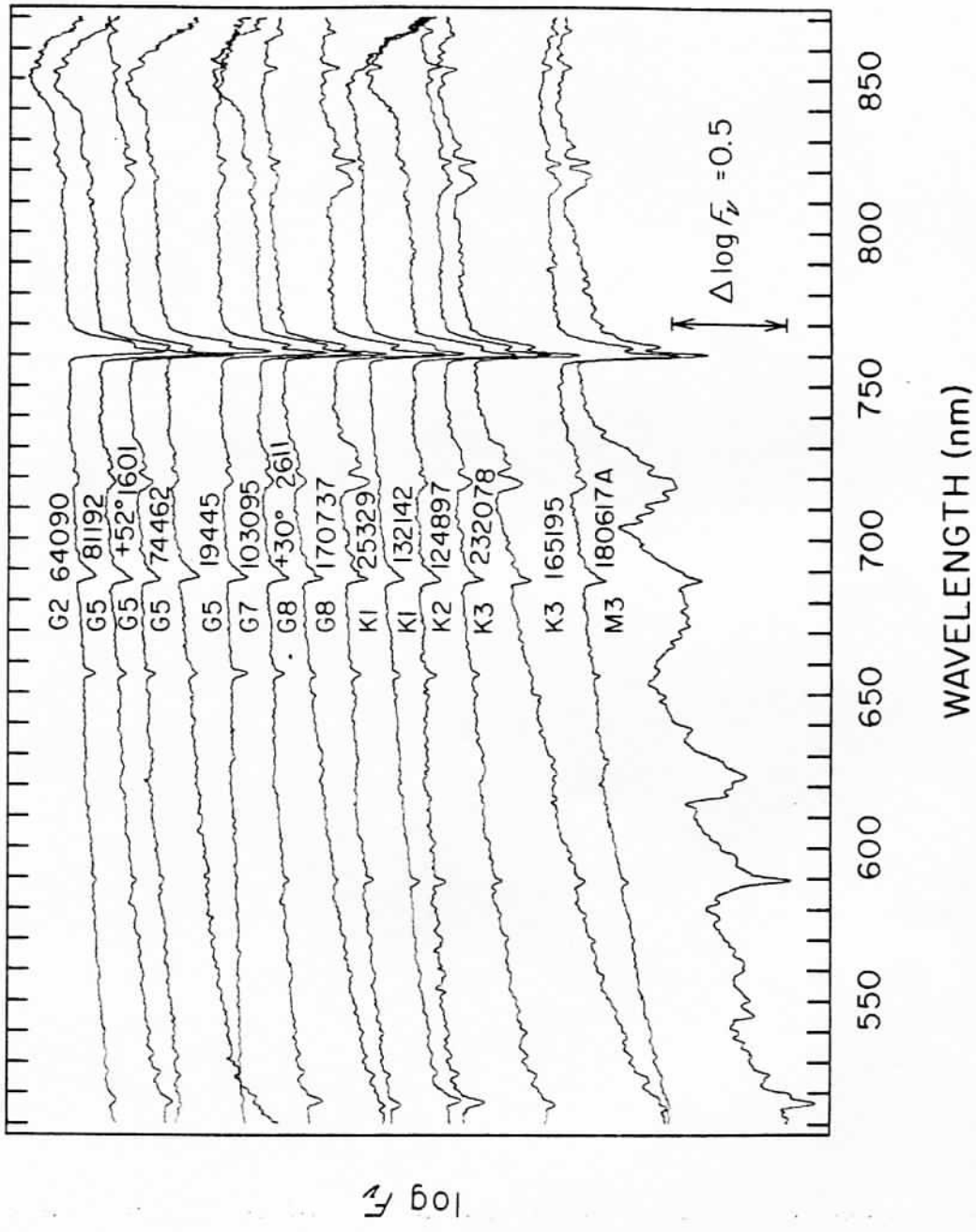
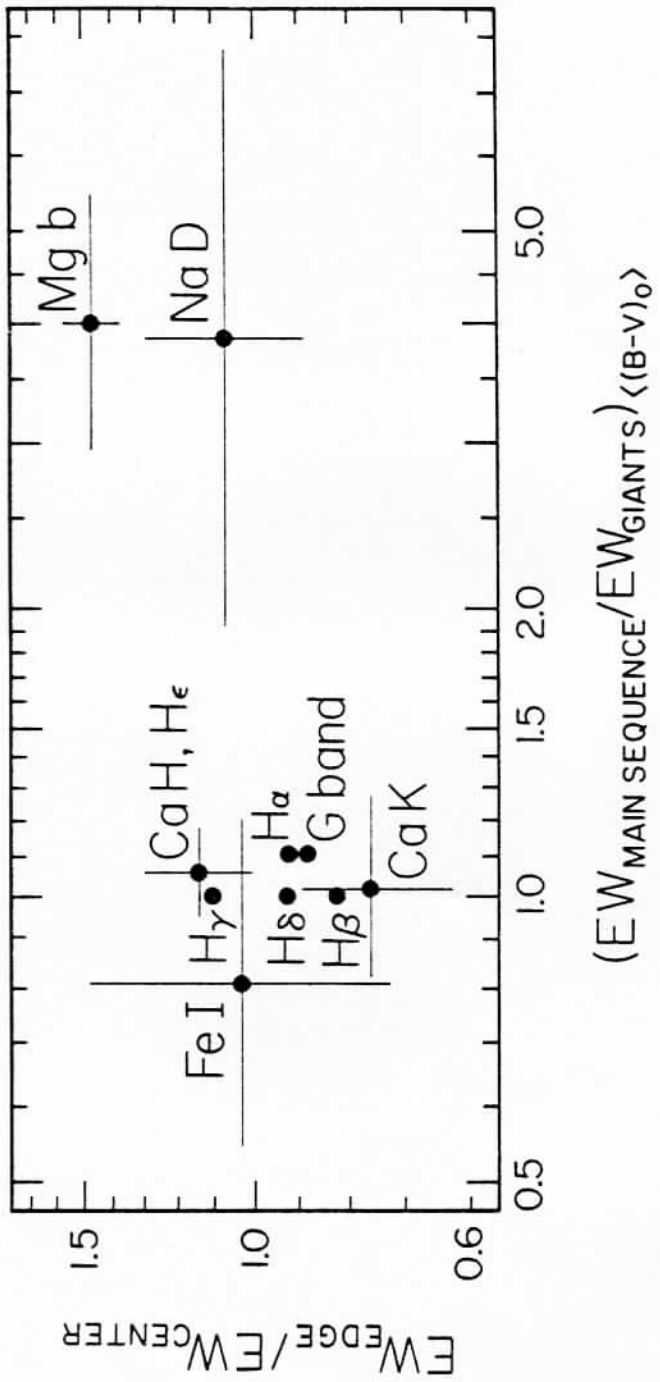


FIGURE 5


Mg b
Na D
CaH, Hε
Hα
G band
Hγ
Hδ
Hβ
Ca K
Fe I
1.5
1.0
0.6
0.5
1.0
1.5
2.0
5.0
EW_EDGE/EW_CENTER
(EW_MAIN SEQUENCE/EW_GIANTS)_<(B-V)_o>

TITLE OF THESIS A DIFFERENTIAL POPULATION SYNTHESIS APPROACH TO MASS SEGREGATION IN M92

Major Professor Kenneth H. Nordsieck, Ph.D.

Major Department Astronomy

Minor(s) Physics

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Publications Davis, J., Tobin, W., and Eaton, J. (1976), Astronomy, 4, No. 8, 40. Jones, T. W., and Tobin, W. (1977), Astrophys. J., 215, 474. Tobin, W. (1978), Bull. Am. Astron. Soc., 10, 409.

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